Recollections of the pi-mu-e-decay parity violation experiment

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(many papers at www.fas.org/RLG)

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For the Brookhaven symposium
Neutrino Helicity at 50
In honor of Maurice Goldhaber

May 2, 2008

- January 1957: “Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon,” R.L. Garwin, L.M. Lederman, and M. Weinrich, (02/15/57).
- Some technology of particle physics experiments from the 1950s.
- August 1957: “Space Properties of the π Meson,” R.L. Garwin, G. Gidal, L.M. Lederman, and M. Weinrich, (12/15/57).
- “The Anomalous Magnetic Moment of the Muon,” G. Charpak, F.J.M. Farley, R.L. Garwin, T. Muller, J. C. Sens, and A. Zichichi (02/01/61 and 06/00/65).

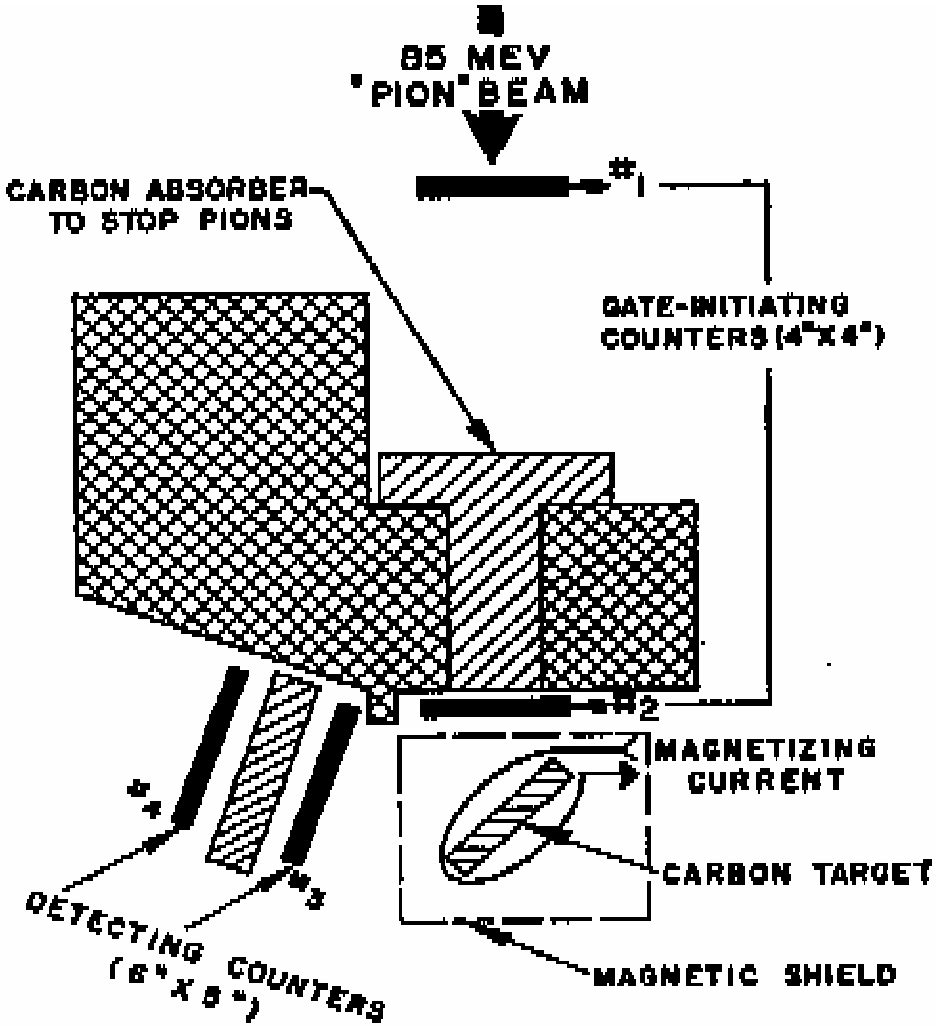

FIG. 1. Experimental arrangement. The magnetizing coil was close wound directly on the carbon to provide a uniform vertical field of 79 gauss per ampere.

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Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

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(Received January 15, 1957)

LEE and Yang[1–3] have proposed that the long held space-time principles of invariance under charge conjugation, time reversal, and space reflection (parity) are violated by the "weak" interactions responsible for decay of nuclei, mesons, and strange particles. Their hypothesis, born out of the $\tau-\theta$ puzzle,[4] was accompanied by the suggestion that confirmation should be sought (among other places) in the study of the successive reactions

$$\pi^+ \rightarrow \mu^+ + \nu, \qquad (1)$$

$$\mu^+ \rightarrow e^+ + 2\nu. \qquad (2)$$

They have pointed out that parity nonconservation implies a polarization of the spin of the muon emitted from stopped pions in (1) along the direction of motion and that furthermore, the angular distribution of electrons in (2) should serve as an analyzer for the muon polarization. They also point out that the longitudinal polarization of the muons offers a natural way of determining the magnetic moment.[5] Confirmation of

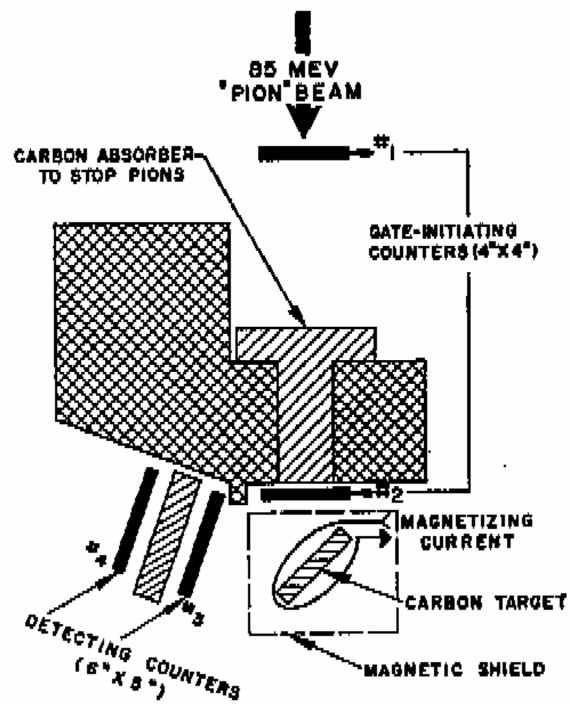

FIG. 1. Experimental arrangement. The magnetizing coil was close wound directly on the carbon to provide a uniform vertical field of 79 gauss per ampere.

$\theta = 100°$. We now apply a small vertical field in the magnetically shielded enclosure about the target, which

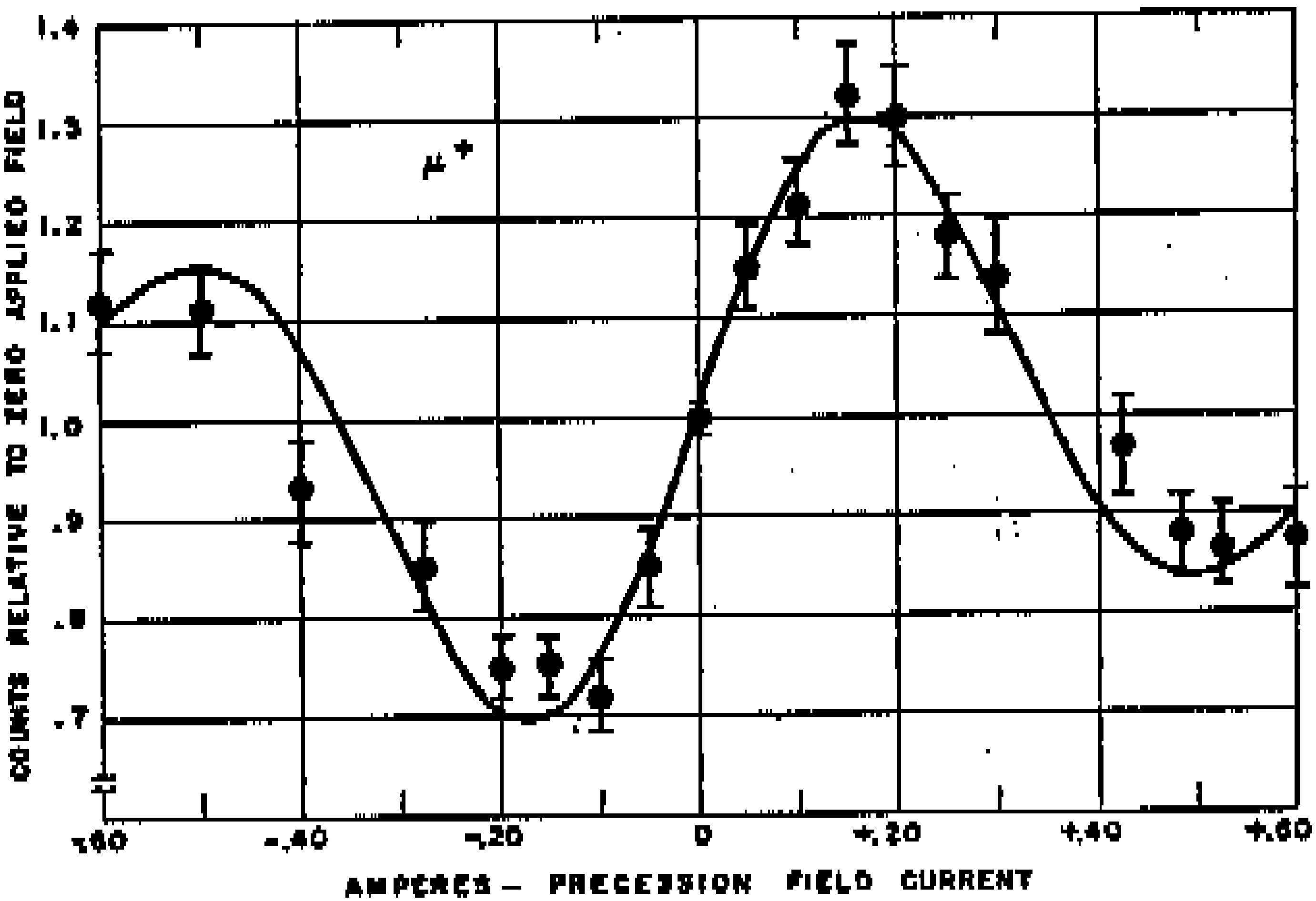

FIG. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

nuclei (even in Pb, 2% of the μ^- decay into electrons[9]), atoms, and interatomic regions.

The authors wish to acknowledge the essential role of Professor Tsung-Dao Lee in clarifying for us the papers of Lee and Yang. We are also indebted to Professor C. S. Wu[6] for reports of her preliminary results in the Co^{60} experiment which played a crucial part in the Columbia discussions immediately preceding this experiment.

* Research supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

† Also at International Business Machines, Watson Scientific Laboratories, New York, New York.

[1] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).

[2] Lee, Oehme, and Yang, Phys. Rev. (to be published).

[3] T. D. Lee and C. N. Yang, Phys. Rev. (to be published).

[4] R. Dalitz, Phil. Mag. **44**, 1068 (1953).

[5] T. D. Lee and C. N. Yang (private communication).

[6] Wu, Ambler, Hudson, Hoppes, and Hayward, Phys. Rev. **105**, 1413 (1957), preceding Letter.

[7] The Fierz-Pauli theory for spin $\frac{3}{2}$ particles predicts a g value of $\frac{2}{3}$. See F. J. Belinfante, Phys. Rev. **92**, 997 (1953).

[8] V. Fitch and J. Rainwater, Phys. Rev. **92**, 789 (1953).

[9] M. Weinrich and L. M. Lederman, *Proceedings of the CERN Symposium, Geneva, 1956* (European Organization of Nuclear Research, Geneva, 1956).

[10] The field interval, ΔH, between peak and valley in Fig. 2 gives the magnetic moment directly by $(\mu\Delta H/s\hbar)(t_1+\frac{1}{2}T)\delta=\pi$, where $\delta=1.06$ is a first-order resolution correction which takes into account the finite gate width and muon lifetime. The 5% uncertainty comes principally from lack of knowledge of the magnetic field in carbon. Independent evidence that $g=2$ (to $\sim$10%) comes from the coincidence of the polarization axis with the velocity vector of the stopped μ's. This implies that the spin precession frequency is identical to the μ cyclotron frequency during the 90° net magnetic deflection of the muon beam in transit from the cyclotron to the 1–2 telescope. We have designed a magnetic resonance experiment to determine the magnetic moment to $\sim$0.03%.

[11] *Note added in proof.*—We have now observed an energy dependence of a in the $1+a\cos\theta$ distribution which is somewhat less steep but in rough qualitative agreement with that predicted by the two-component neutrino theory $(\mu\rightarrow e+\nu+\bar{\nu})$ without derivative coupling. The peak-to-valley ratios for electrons traversing 9.3 g/cm², 15.6 g/cm², and 19.8 g/cm² of graphite are observed to be 1.80±0.07, 1.84±0.11, and 2.20±0.10, respectively.

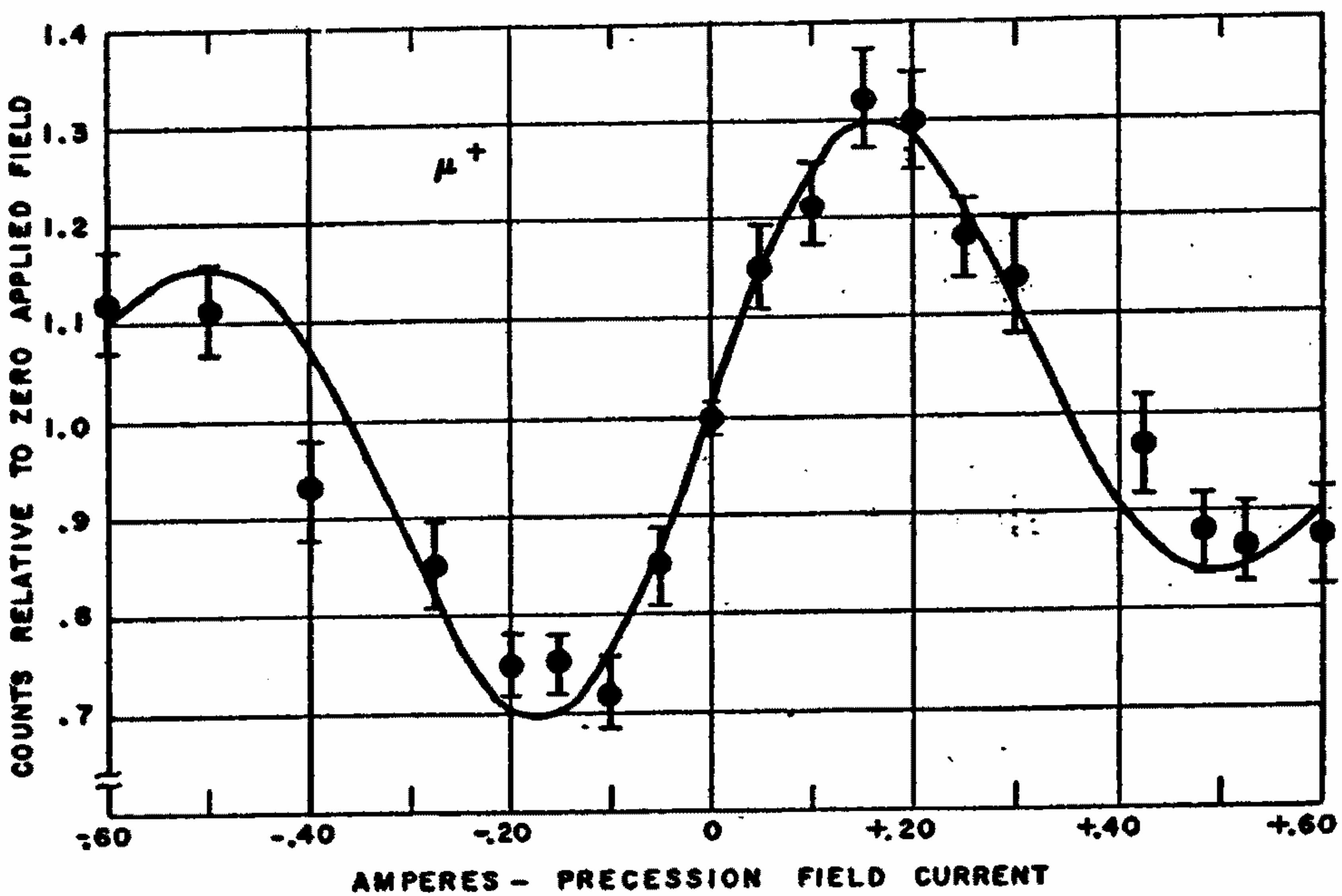

Fig. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

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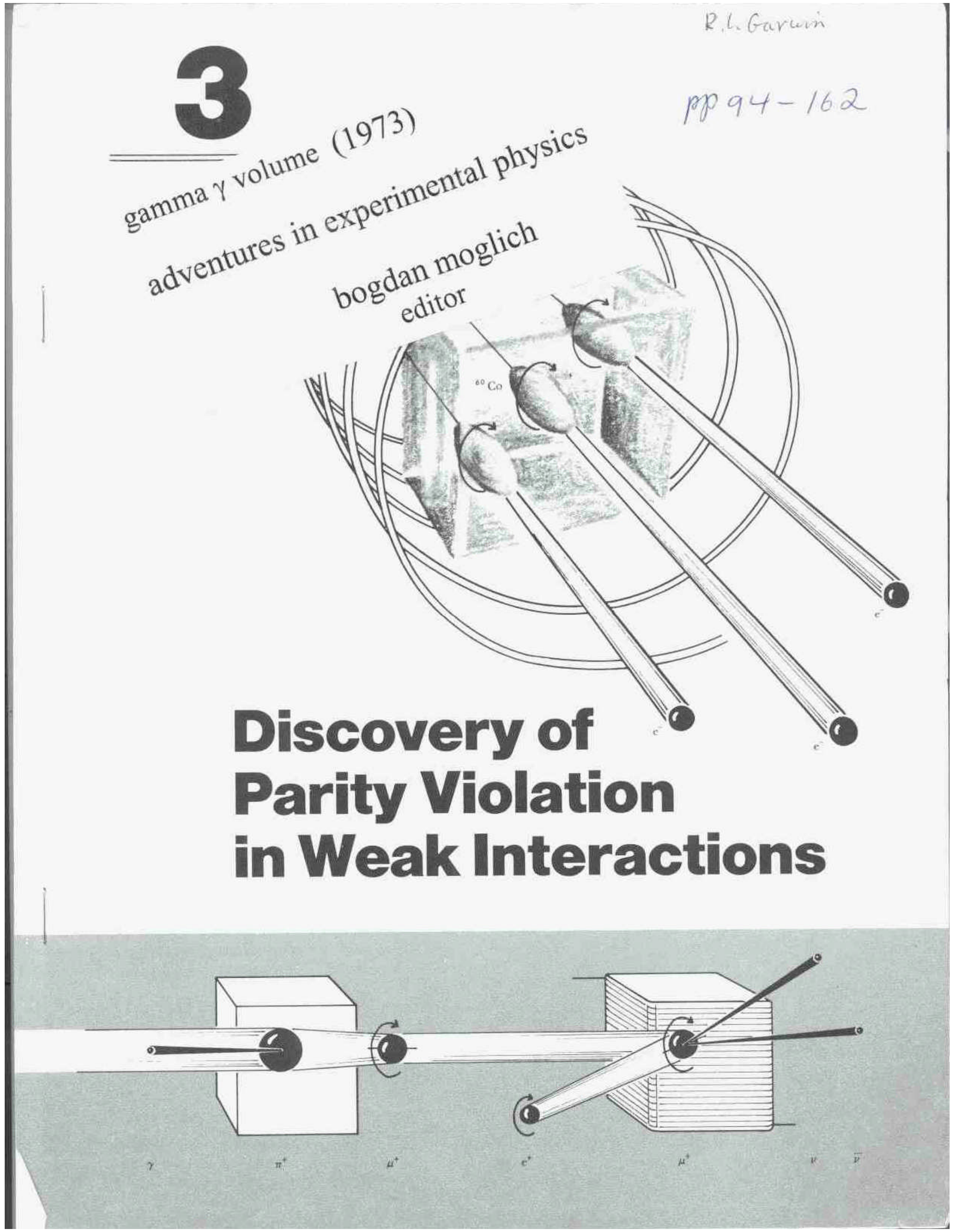
R.L. Garwin
pp 94-162
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gamma γ volume (1973)
adventures in experimental physics
bogdan moglich
editor
Discovery of
Parity Violation
in Weak Interactions

The decay electrons emerging in the backward direction after the rf pulse was over were counted; the "peak" rate was obtained for no transition, a decrease in rate

02/01/58 T. Coffin, R.L. Garwin, S. Penman, L.M. Lederman, and A.M. Sachs.

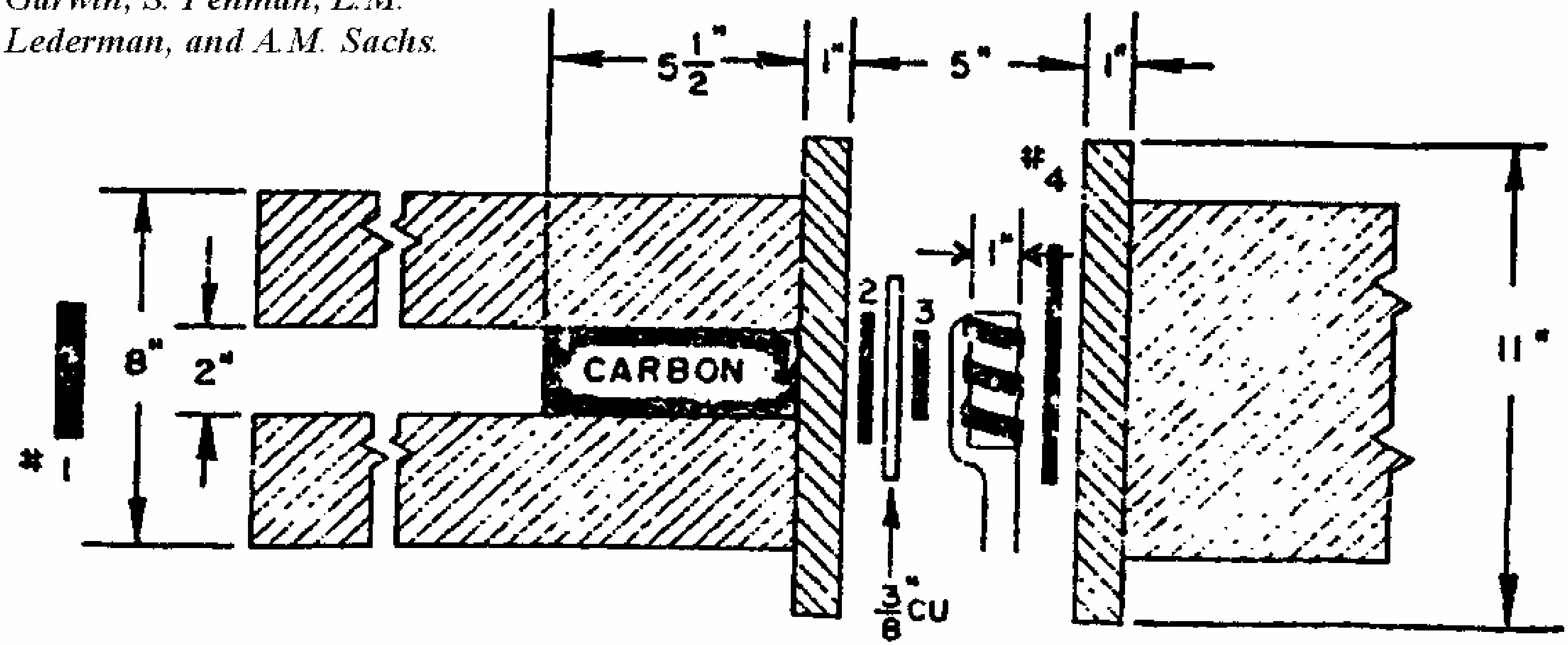

FIG. 1. Experimental arrangement.

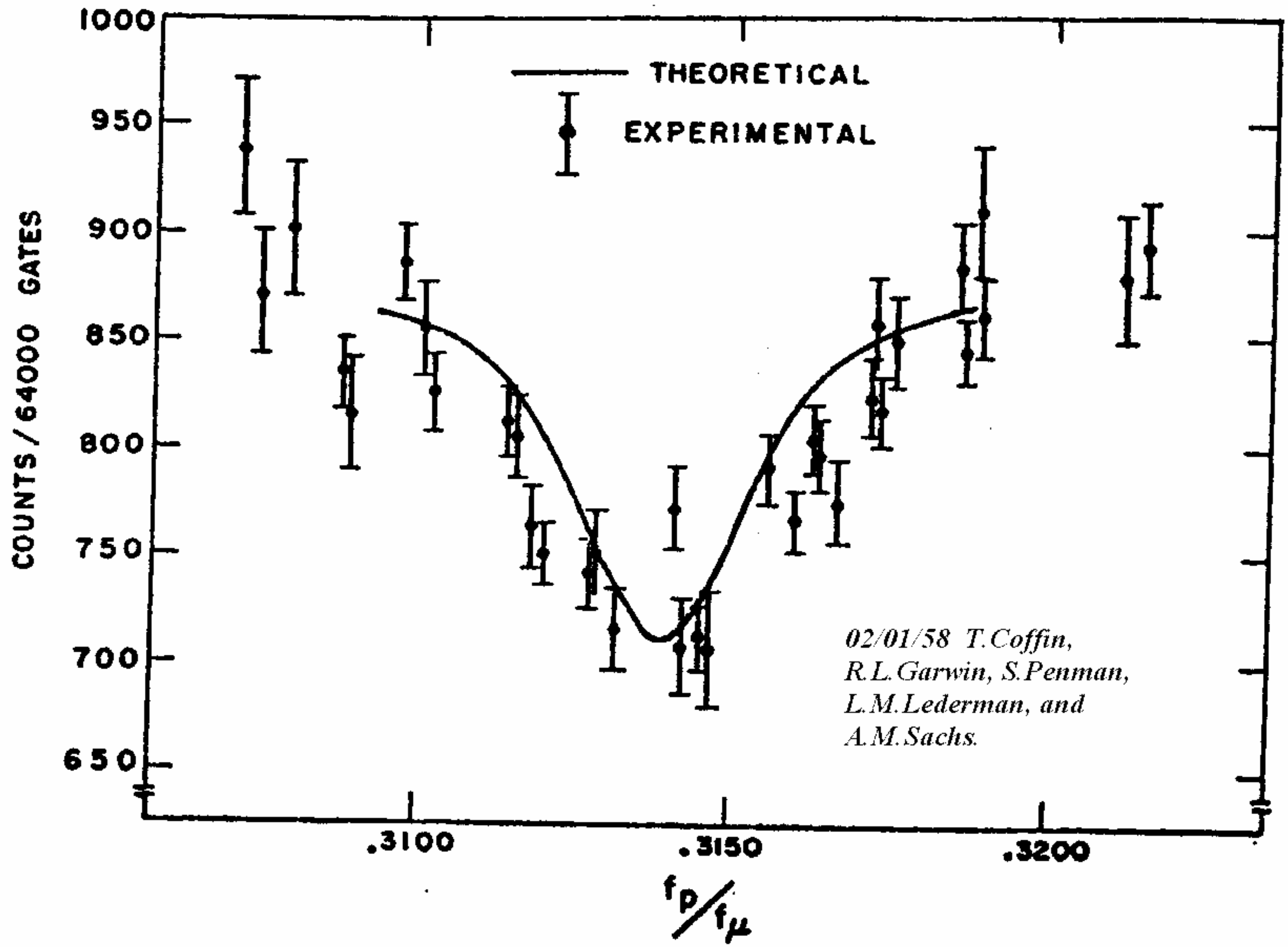

FIG. 5. Theoretical line shape and composite of the experimental points.

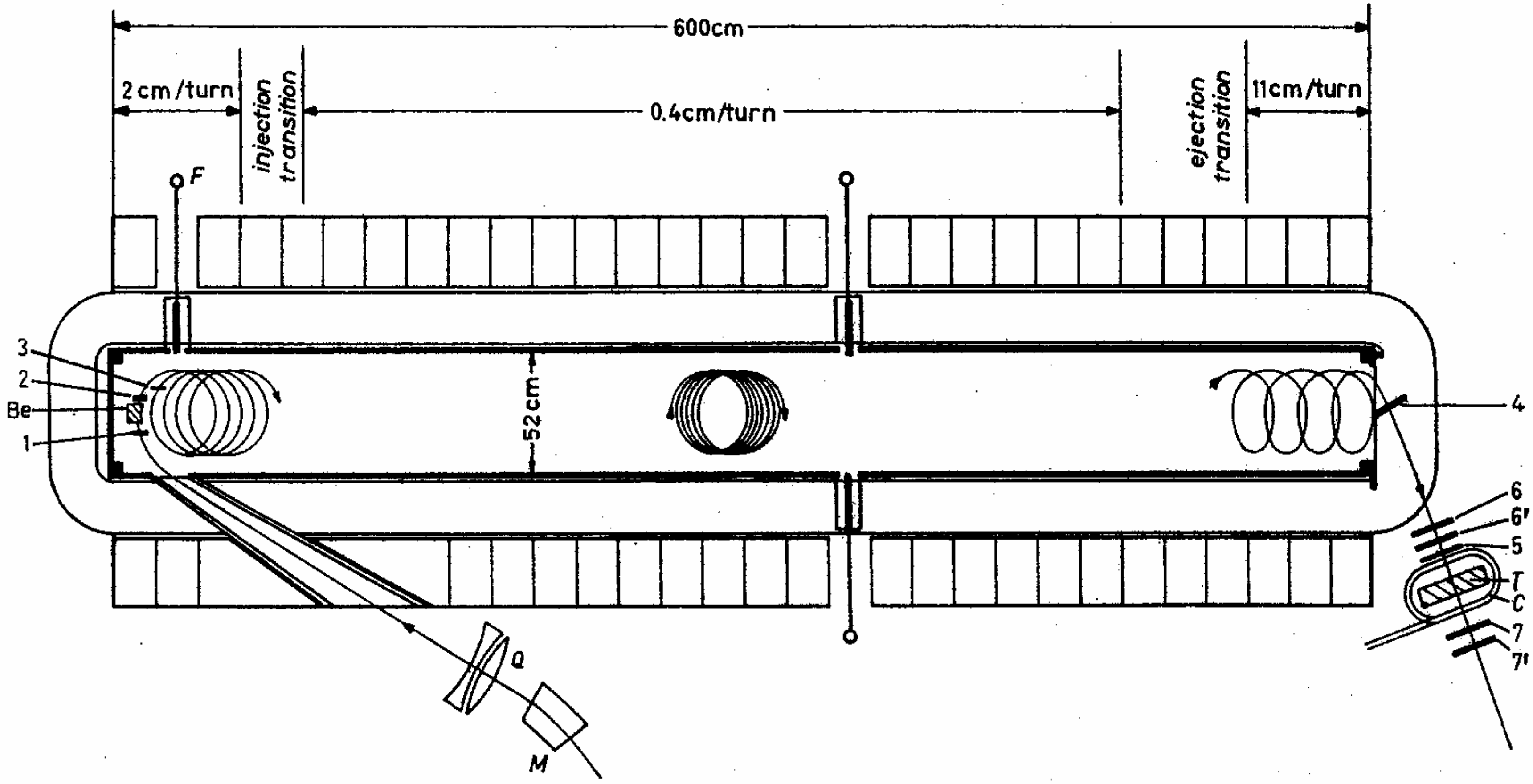

Fig. 1. – General view of the apparatus, showing magnet of pole surface $(600 \times 52)\ \text{cm}^2$. Muons, deflected by the bending magnet M and focused by the quadrupole pair Q enter the magnet via a shielded channel. After slowing down in the beryllium moderator Be they describe many turns in the field. The quasi-circular orbit is slowly displaced by the field gradient (2 cm/turn in the *injection* region, 0.4 cm/turn in the *storage* region, and 11 cm/turn in the final *ejection* region). Muons ejected from the magnet are stopped in target T of the polarization analyser where the spin direction is determined by recording the decay electrons. Injected muons are indicated by the counter signature 123. Ejected muons by the signature $466'\,5\bar{7}$. Decay electrons by $66'\,4(\overline{77'})$ and $77'\,\bar{4}(\overline{66'})$. The time of flight of muons between counters 2 and 4 is recorded.

G. CHARPAK, *et al.*
16 Giugno 1965
Il Nuovo Cimento
Serie X, Vol. 37, pag. 1241-1363

123pps.

The Anomalous Magnetic Moment of the Muon.

G. Charpak (*), F. J. M. Farley, R. L. Garwin (**), T. Muller (***), J. C. Sens and A. Zichichi

CERN - Geneva

(ricevuto il 18 Settembre 1964)

Summary. — The anomalous part of the gyromagnetic ratio, $\mathbf{a} = \frac{1}{2}(g-2)$ of the muon has been measured by determining the precession $\theta = \mathbf{a}\omega_0 \overline{B} t$ for 100 MeV/c muons as a function of storage time t in a known static magnetic field of the form $B = B_0(1 + ay + by^2 + cy^3 + dy^4)$. The result is $\mathbf{a}_{\text{exp}} = (1162 \pm 5) \cdot 10^{-6}$ compared with the theoretical value $\mathbf{a}_{\text{th}} = \alpha/2\pi + 0.76\,\alpha^2/\pi^2 = 1165 \cdot 10^{-6}$. This agreement shows that the muon obeys standard quantum electrodynamics down to distances ~ 0.1 fermi. Details are given of the methods used to store muons for $\sim 10^3$ turns in the field, and of measuring techniques and precautions necessary to achieve the final accuracy. Some of the methods of orbit analysis, magnet construction shimming and measurement, polarization analysis, and digital timing electronics may be of more general interest.

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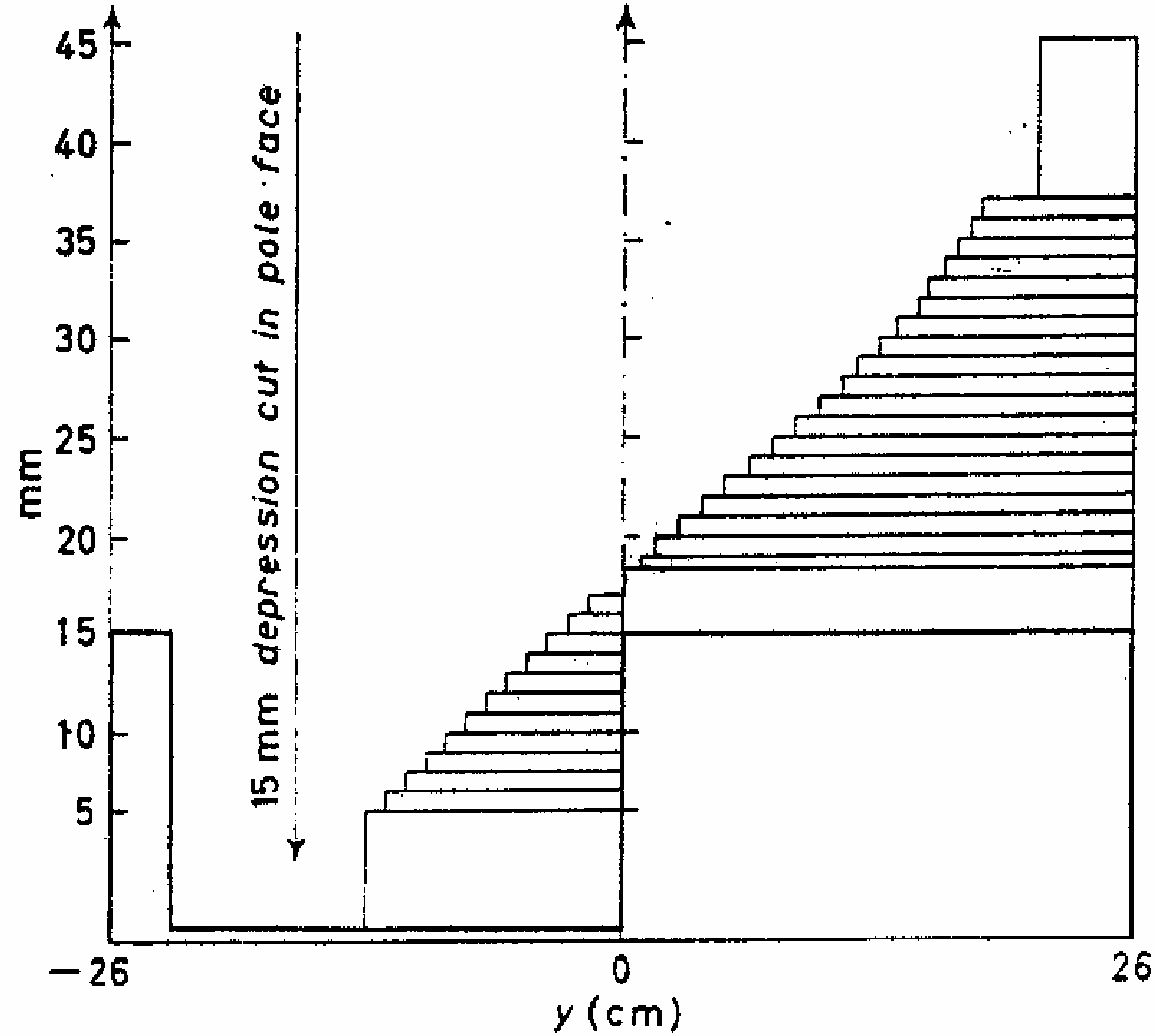

Fig. 19. – Shims for ejection field. In order to establish the desired gradient while maintaining the field constant at $y=0$, it was necessary to cut away iron from the pole face on the weak-field side.

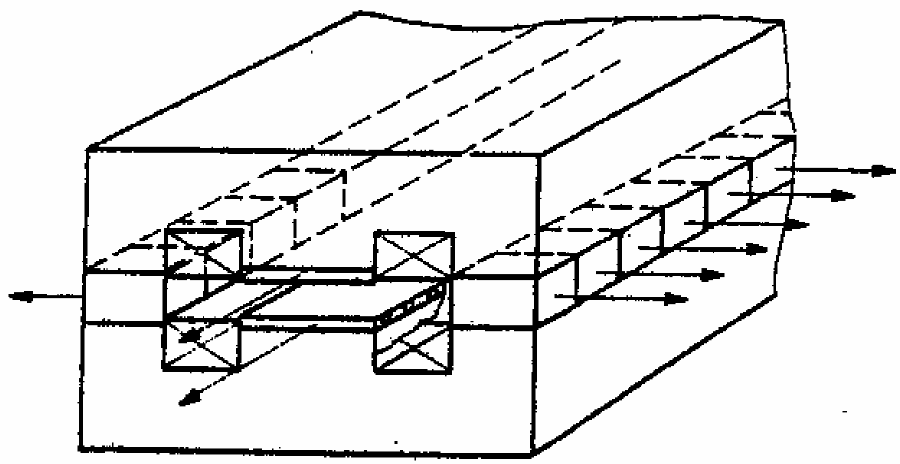

Fig. 23. – Overall view of the magnet showing the removable iron blocks ($20\times20\times\times31\ \text{cm}^3$) in the yokes, and the removable top and bottom pole pieces (5 cm thick). To remove the poles the lower pole was first raised by hydraulic jacks via vertical push rods passing through the lower half of the magnet. An assembly of rollers was then introduced below this pole, and finally the upper and lower poles were rolled out of the magnet together onto a special table also equipped with rollers. Arrows indicate those parts of the magnet which can be taken out.

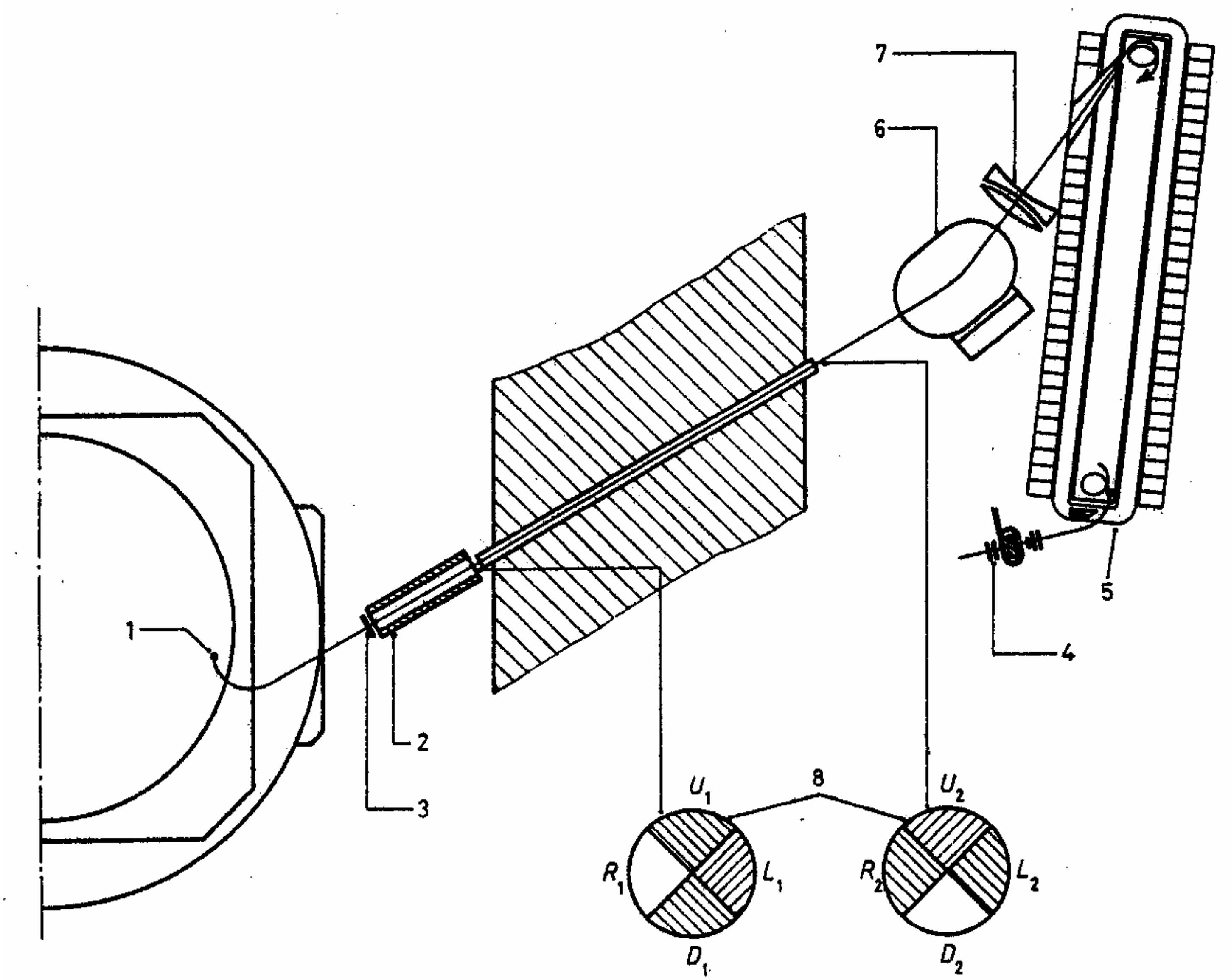

Fig. 48. – Final layout of experiment, showing cyclotron, solenoid, pipe through shielding wall with the possibility of dividing each end of the pipe into quadrants to study beam structure. Note the lead scattering foil added to scramble the muons into different beam cells, thus reducing spin-angle/position correlations. 1) target; 2) solenoid; 3) lead foil; 4) polarization analyser; 5) storage magnet; 6) bending magnet; 7) quadrupole lenses.

noid of length 200 cm (see Fig. 48). The field and length of the solenoid are chosen to rotate the transverse component of the muon spin by 90°, whereas the component along the axis of the solenoid is not affected. For our 150 MeV/c muons and 200 cm available length, a magnetic field $B = 3\,950$ G is required to obtain 90° rotation.

** Figure 48 was here **

The polarization was re-measured with the *solenoid on* as a function of range with the results of Table VI, which are plotted in Fig. 49. The results of a least-squares fit to this data are

(86) θ_{beam} (at range $X = 10$ cm carbon) $= -(\ 0.5 \pm 12)$ mrad ,

(87) and slope $(\mathrm{d}\theta/\mathrm{d}R)_{\text{beam}}$ $= -(19 \pm 12)$ mrad/cm .

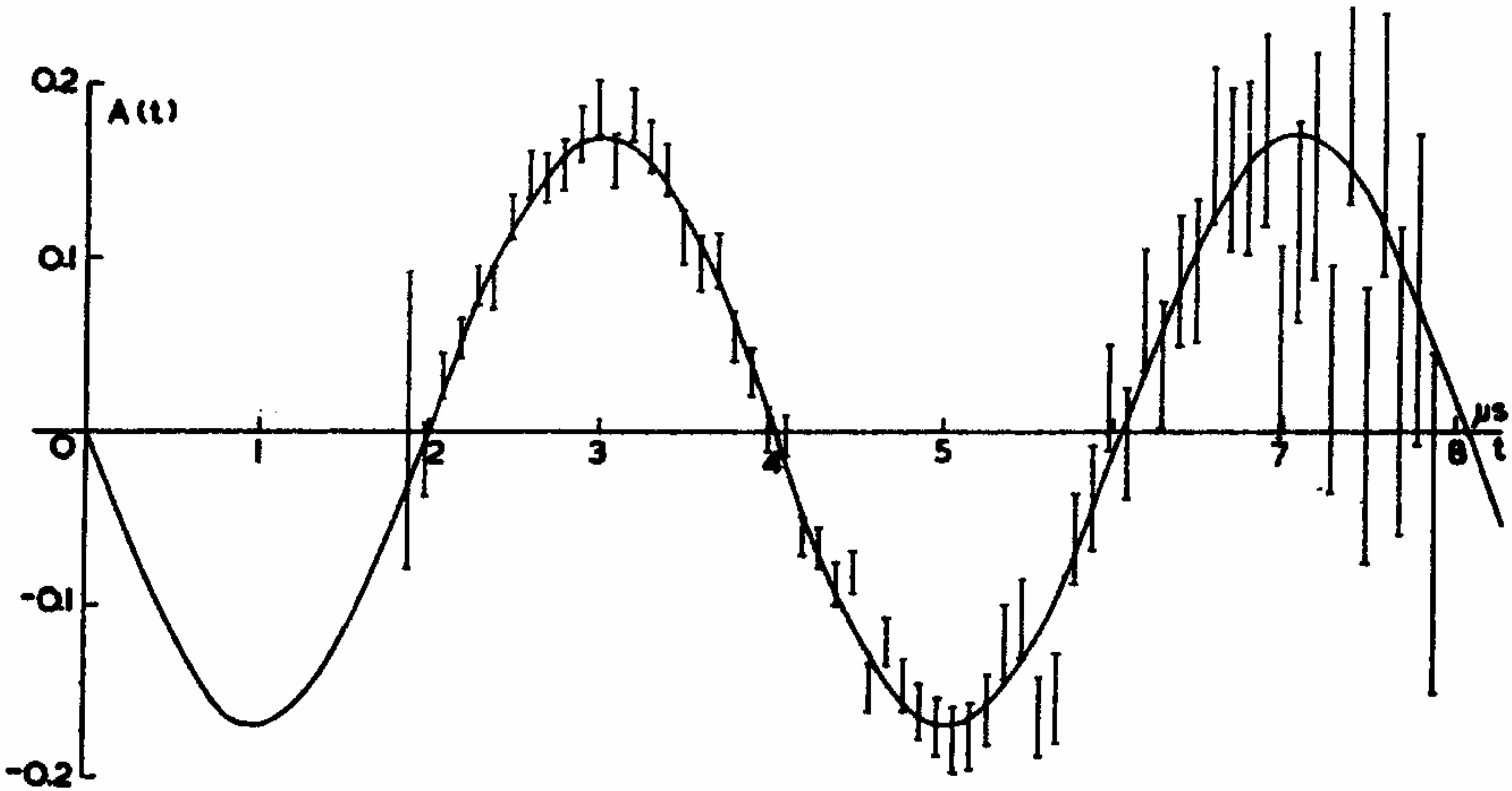

Fig. 4. Electron asymmetry $A(t)$ for $\pm$ 90° flipping (combined data from forward and backward telescopes) as a function of storage time t with curve showing the best fit obtained by varying A_0 and a in eq. (8).

Table 3
Anomalous moment evaluation for separate runs of $A(t)$ vs. t. The distribution of the individual results about the combined value 1162 is statistical, $\chi^2 = 20.3$, expected value 19.3.

Run	$a_{exp} \times 10^6$	χ^2 for this fit (expectation value = 58)	Difference from final value of a_{exp}	Statistical error $\times 10^6$
1	1169	65	+ 7	13
2	1155	70	- 7	14
3	1135	58	-27	15
4	1165	49	+ 3	16
5	1149	76	-13	19
6	1183	50	+21	14
7	1162	53	0	13
8	1154	61	- 8	15
9	1197	68	+35	16
10	1132	72	-30	14
11	1162	86	0	19
12	1178	50	+16	16
13	1133	62	-29	23
14	1160	63	- 2	13
15	1154	50	- 8	36
16	1174	71	+12	16
17	1150	57	-12	26
18	1145	51	-17	17
19	1146	48	-16	23
20	1181	70	+19	19
21	1173	66	+11	27

→ 1162 ± 5

If now the copper shield diameter is so chosen as to make an approximate impedance match with some

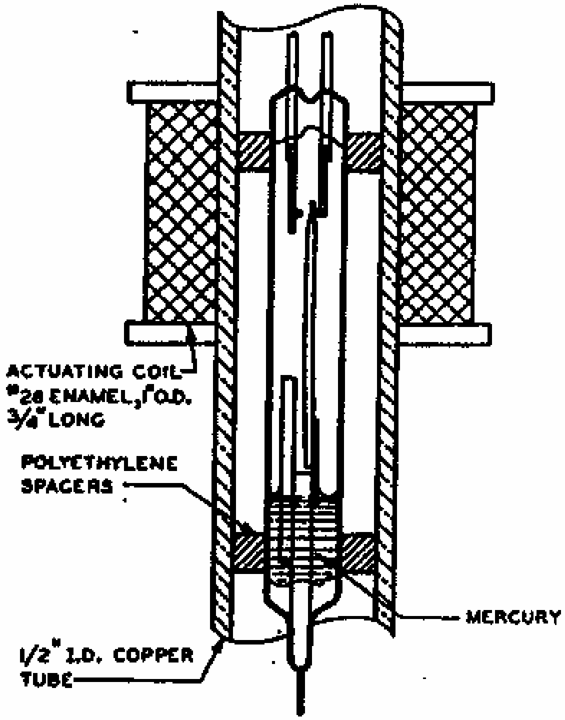

FIG. 1. Rapid coaxial switch.

[1] The glass-enclosed switch is taken from a Western Electric D-168479 synchronous relay.

The indicated pulse heights hold, of course, only if the system is matched in impedance at each point. Thus, if an output is not being used, it must be terminated in its characteristic impedance to avoid reflections. The system impedance used in the pulser here constructed is 75 ohms, for which no constant-impedance connectors are available. Accordingly, the AN-83 series connectors

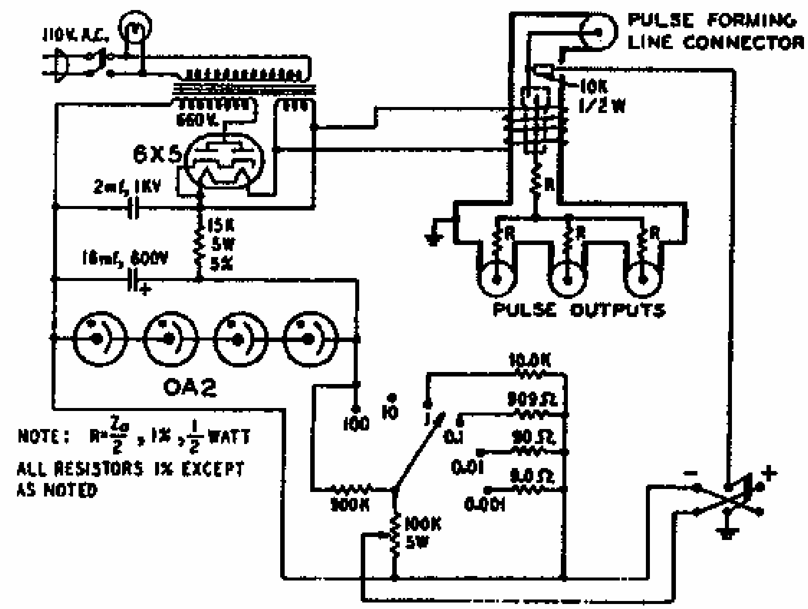

FIG. 2. Pulser schematic.

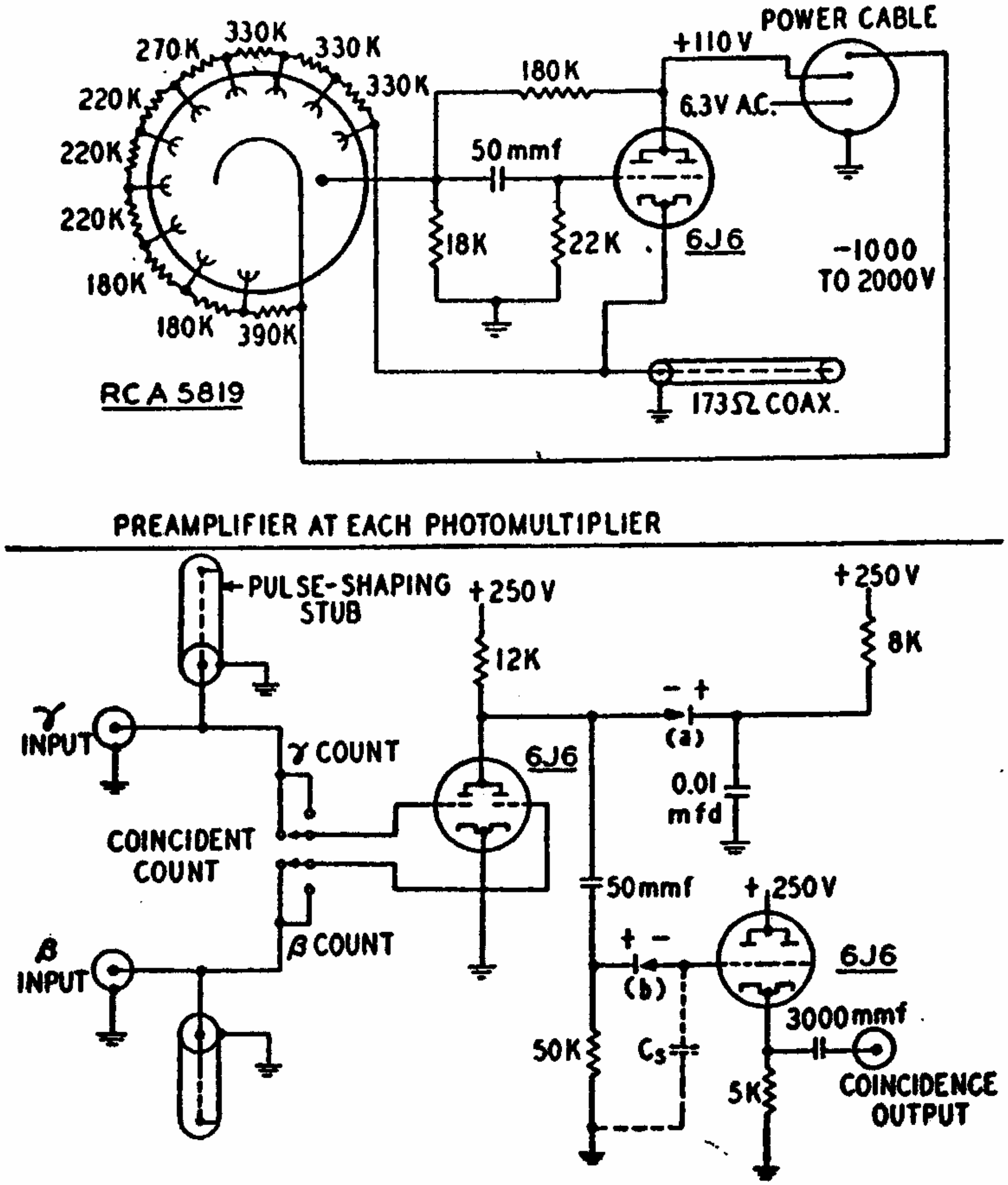
POWER CABLE
+110 V
6.3V A.C.
270 K
330K
330 K
330K
180K
220K
220K
220K
180K
180K
390K
50 mmf
18K
22K
6J6
-1000
TO 2000V
RCA 5819
173Ω COAX.
PREAMPLIFIER AT EACH PHOTOMULTIPLIER
PULSE-SHAPING
STUB
+250V
12K
+250V
8K
γ
INPUT
γ COUNT
6J6
(a)
0.01
mfd
COINCIDENT
COUNT
50mmf
+250V
β
INPUT
β COUNT
(b)
6J6
3000mmf
50K
C_s
5K
COINCIDENCE
OUTPUT

FIG. 1.

Reprinted from THE REVIEW OF SCIENTIFIC INSTRUMENTS, Vol. 21, No. 6, 569, June, 1950
Printed in U. S. A.

A Useful Fast Coincidence Circuit

R. L. GARWIN
Institute for Nuclear Studies and Department of Physics, University of Chicago, Chicago, Illinois

February 17, 1950

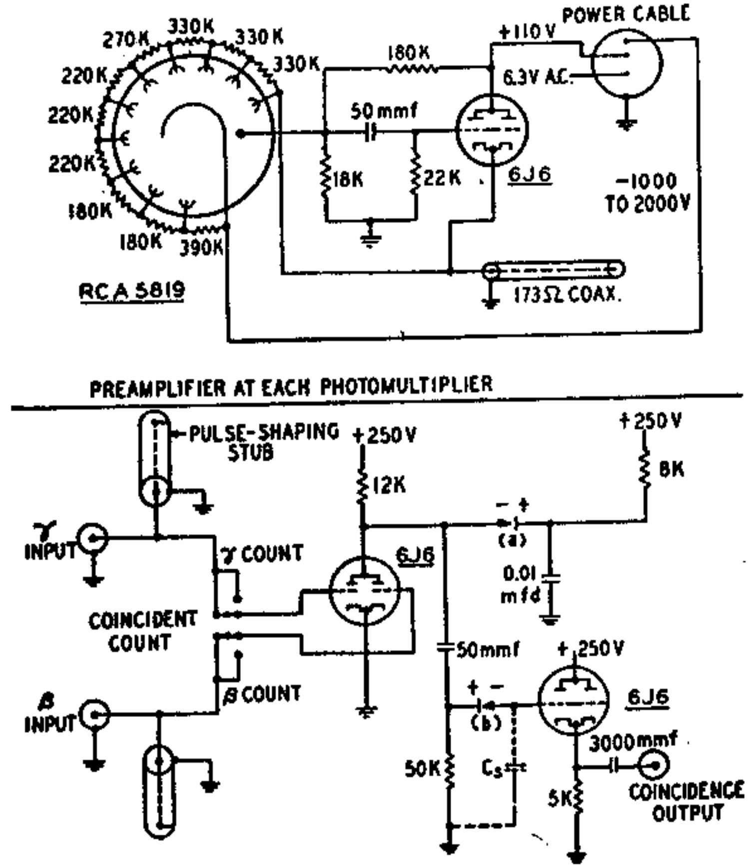

FIG. 1.

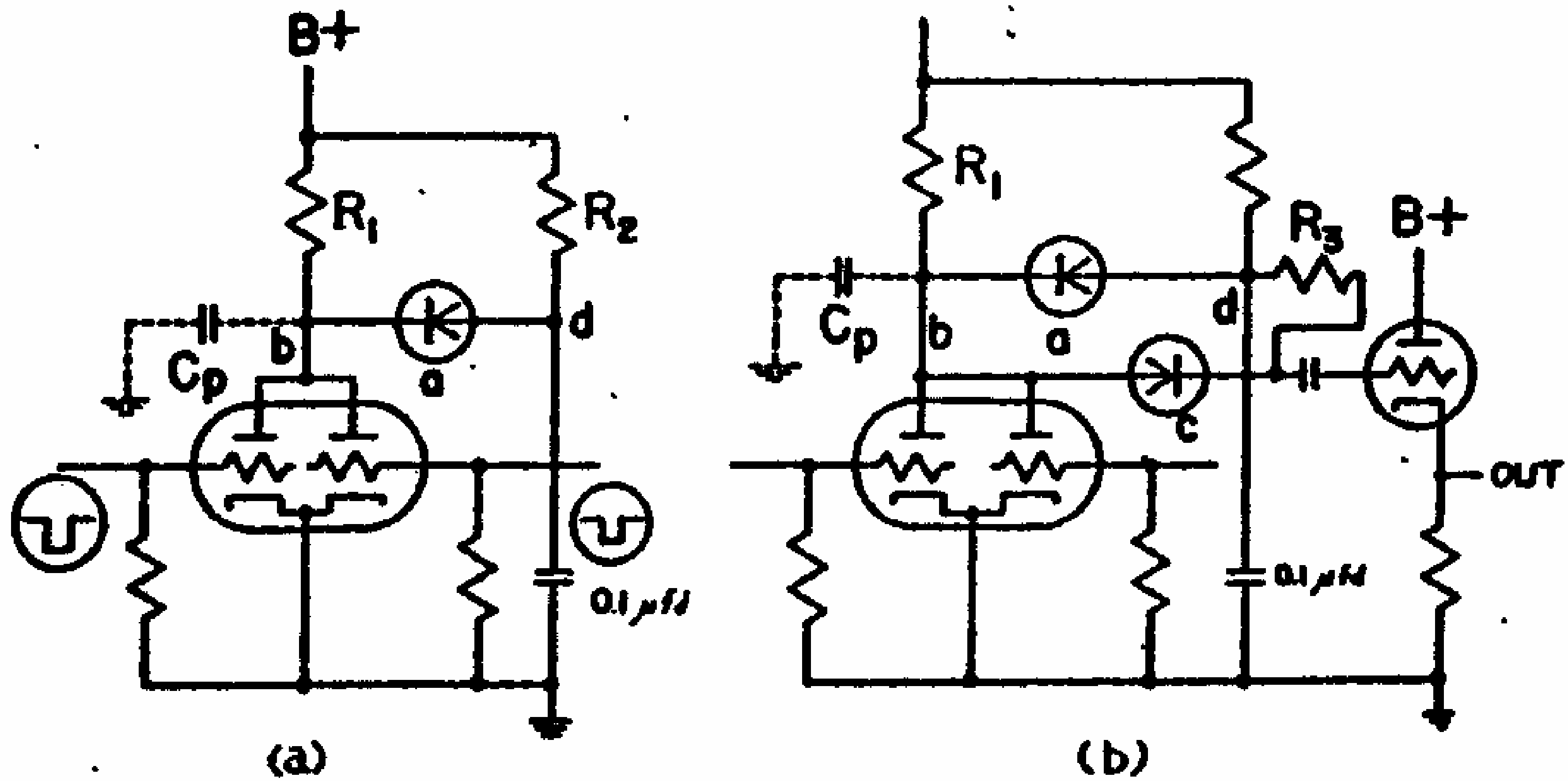

FIG. 1. (a) Modified Rossi coincidence circuit. (b) Same with self-biased discriminator.

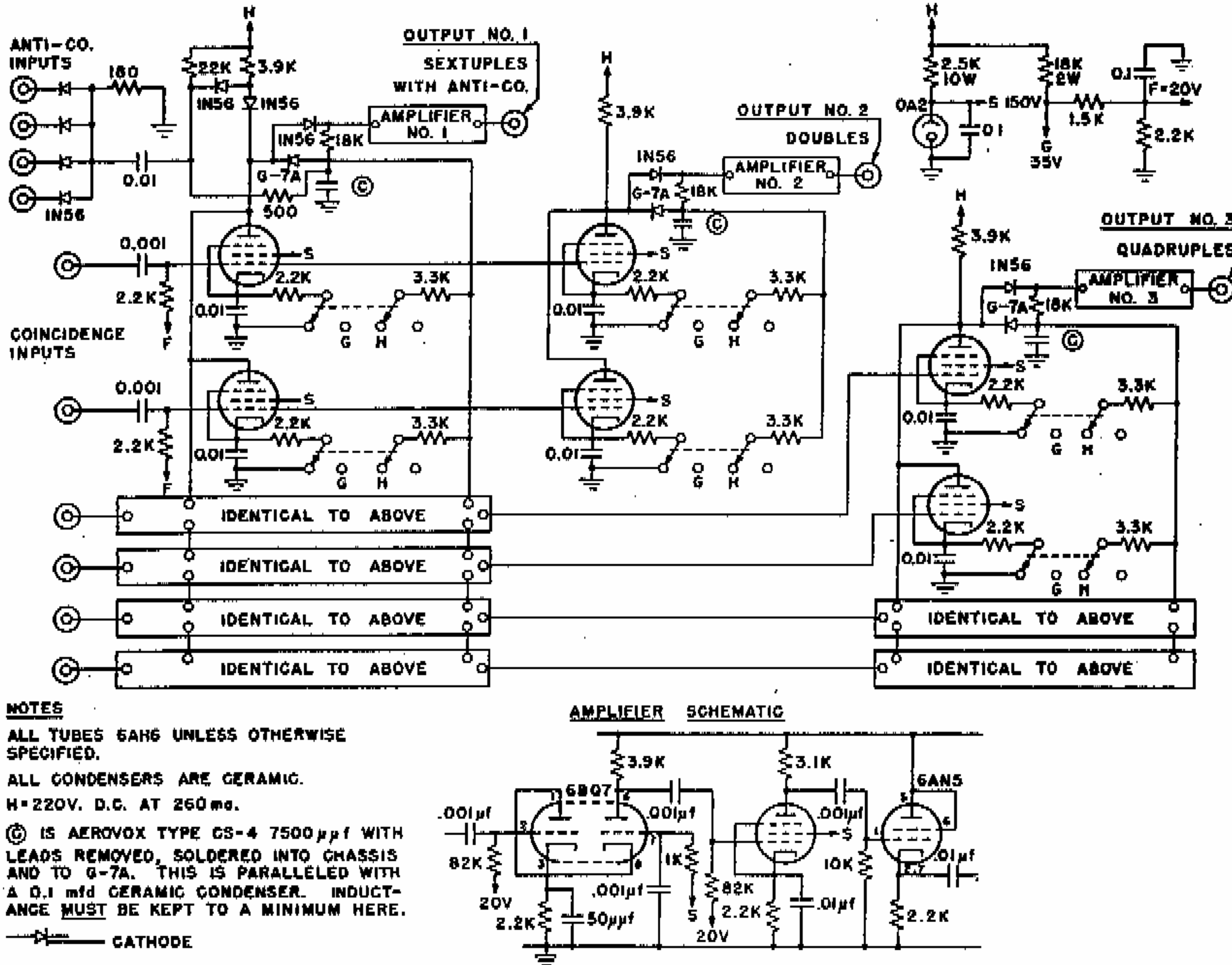

FIG. 4. Fast coincidence-anticoincidence analyzer schematic.

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Printed in U. S. A.

The Design of Liquid Scintillation Cells*

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Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois
(Received April 18, 1952)

NEW types of liquid scintillator cells have been developed here, of such excellence that they have entirely supplanted fast crystal scintillators. The new cells are made possible by the discoveries that the scintillation fluid (3 g terphenyl and 10 mg

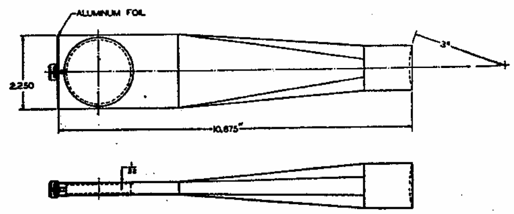

Fig. 1.

diphenylhexatriene[1,2] per liter of phenylcyclohexane) does not dissolve appreciable amounts of Lucite (first observed here by G. Yodh) and that small amount that does dissolve has no effect on the scintillations. The diphenylhexatriene increases the photomultiplier response by a factor two, by changing the emitted spectrum from the invisible ultraviolet to the blue, thus reducing self-absorption in the liquid and in the Lucite light pipes and matching the 5819 photosensitivity more accurately. Clearly, any phenylcyclohexane sample that looks water-white in the depth to be used does not absorb appreciably the spectrum emitted from a scintillation.

Figure 1 shows a 2-in. diameter by 1-cm thick liquid cell with $\frac{1}{32}$-in. Lucite windows. The windows are attached with glacial acetic acid, which makes an optically clear joint unaffected by this scintillation fluid. The cell shown is polished on all surfaces and acts as a light pipe to conduct the light from the scintillation to the 5819 photomultiplier which is attached by means of a film of grease to the spherical depression at the left. It is easy to show that one can conduct essentially all the light traveling by total internal reflection along a light pipe of any cross-sectional shape into another light pipe of any other cross-sectional form, so long as the cross-sectional *areas* of the two light pipes are equal.[3] The only requirement on the transition section is that it be adiabatic, i.e., have small angles of taper and maintain constant area. The construction of Fig. 1 is an approximation to the adiabatic taper between the rectangular cross section and the circular. It is estimated that 25 percent of the light emitted in a scintillation arrives at the photocathode[4] (with aluminum foil attached by a film of grease to the transverse surface at the right end). Figure 2 shows the success of this type of construction. We plot the relative dc current observed at the anode of the photomultiplier as a function of position of a beam of gamma-rays perpendicular to the cell. The gamma-rays are from 150 mc of Co^{60} collimated by 4 in. of lead to a $\frac{3}{16}$-in. diameter beam.

It is evident that the optical efficiency is uniform to 1 percent over the volume of the cell. The fall-off at the edge is the result of the finite size of the gamma-ray beam and the finite range of the Compton recoils. The pulse-height spread from minimum ionization particles passing through the cell is about ±5 percent, allowing one to discriminate among particles by their velocity, i.e., specific ionization. This pulse-height spread is entirely a result of the

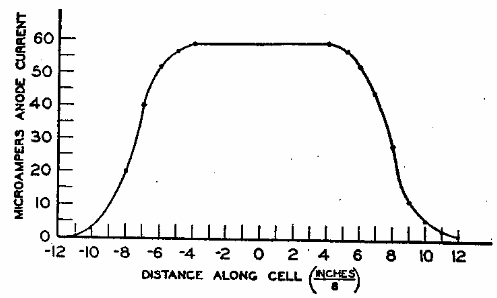

Fig. 2.

statistical fluctuations in the finite number of photoelectrons from the multiplier cathode.

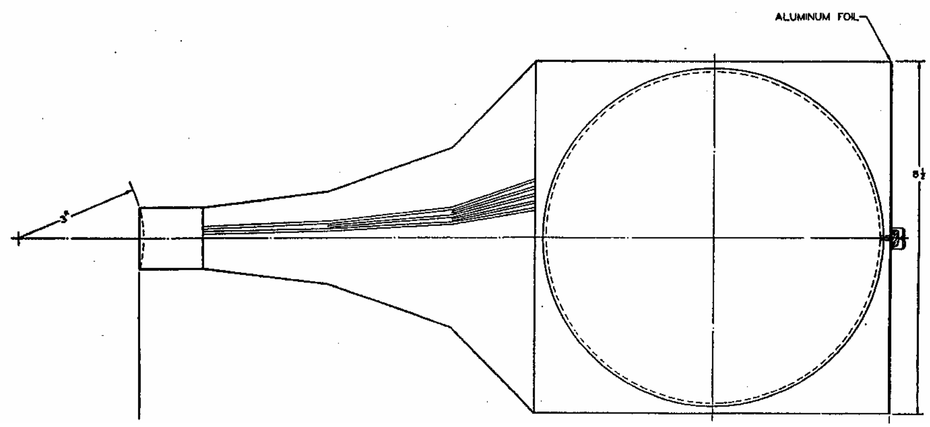

Fig. 3.

he Collection of Light from Scintillation Counters

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f Watson Laboratory, Columbia University,
New York 27, New York

(Received June 14, 1960)

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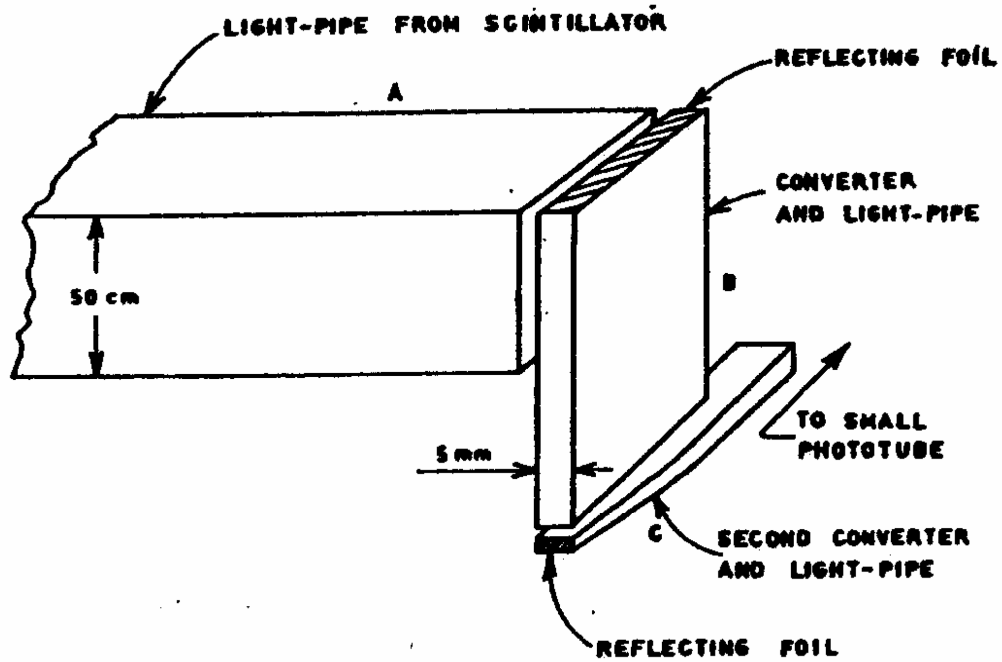

FIG. 1. Light from the light-pipe or scintillating vat (A) strik
converter (B), in which it produces fluorescent light of slightly
photon energy. Some of this light, being isotropic, can now be
along the converter without further loss; and, in principle, c
used a second time to produce fluorescence in the second con
(C) to concentrate further the light onto a small phototube.

PHYSICAL REVIEW VOLUME 108, NUMBER 6 DECEMBER 15, 1957

Space Properties of the π Meson*

R. L. GARWIN,† G. GIDAL, L. M. LEDERMAN, AND M. WEINRICH
Columbia University, New York, New York

(Received August 28, 1957)

Measurements have been made of the circular polarization of the decay photons emitted from an "unpolarized" sample of π^0 mesons, the asymmetric emission of μ^+ mesons from cyclotron-produced π^+ mesons, and the asymmetric emission of μ^+ mesons from π^+ mesons produced in weak interactions. All three experiments give negative results.

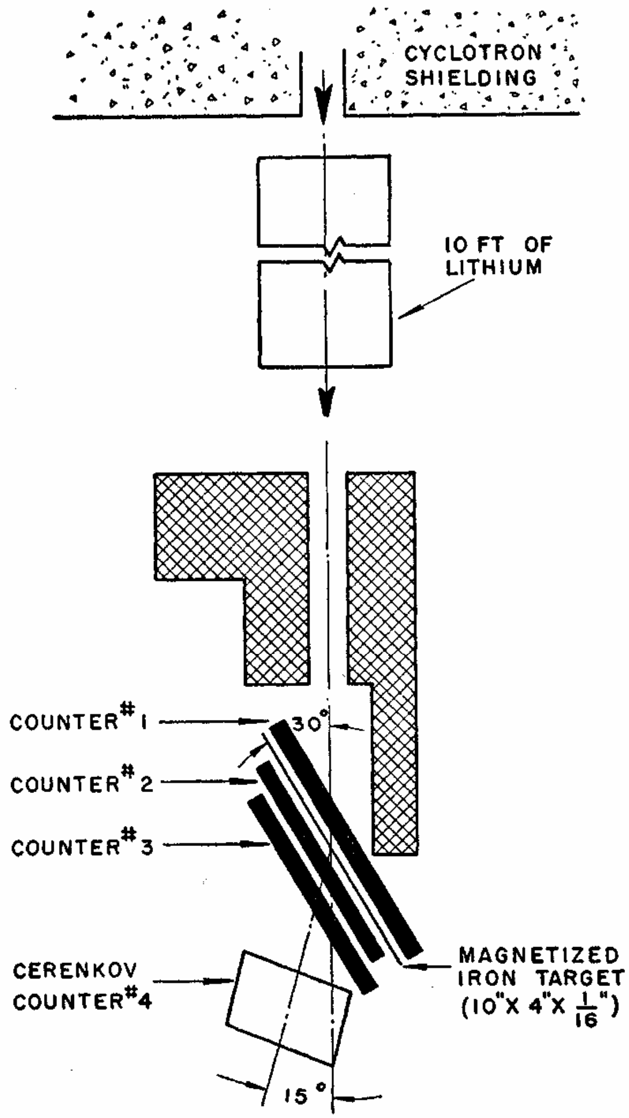

FIG. 1. Apparatus for counting Compton recoils from high-energy photons. Reversal of magnetization in the iron plate allows a measurement of the degree of circular polarization of the π°-decay photons. Pairs are rejected by using as the "event" counts $(\overline{1234}\overline{3'})$ with pulses 3′ being all those pulses from 3 larger than a given discriminator setting.

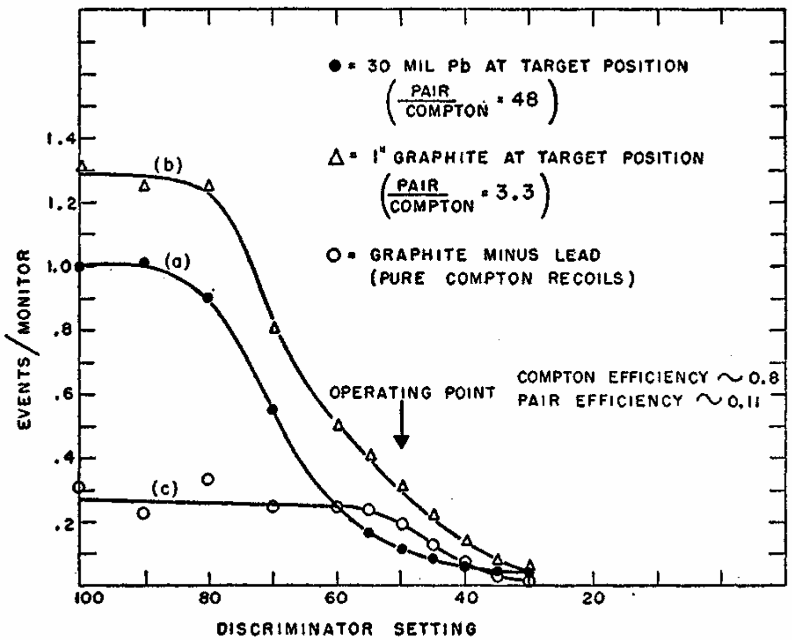

FIG. 3. Pulse-height spectra from (a) lead in target position (pure pairs), (b) carbon in target position (pairs $+\sim 25\%$ Comptons), and (c) the difference between (b) and (a). Curve (c) shows no pair characteristics and is clearly the response of our apparatus to pure Compton recoils.

From the observed ratio (1.001 ± 0.004) of counts with field forward to field backward, and from our calibration which shows that from iron under our requirements there still remain twice as many pairs being counted as Comptons, we find a π^0 photon polarization

$$(P=2.0\pm 9.0\%).$$

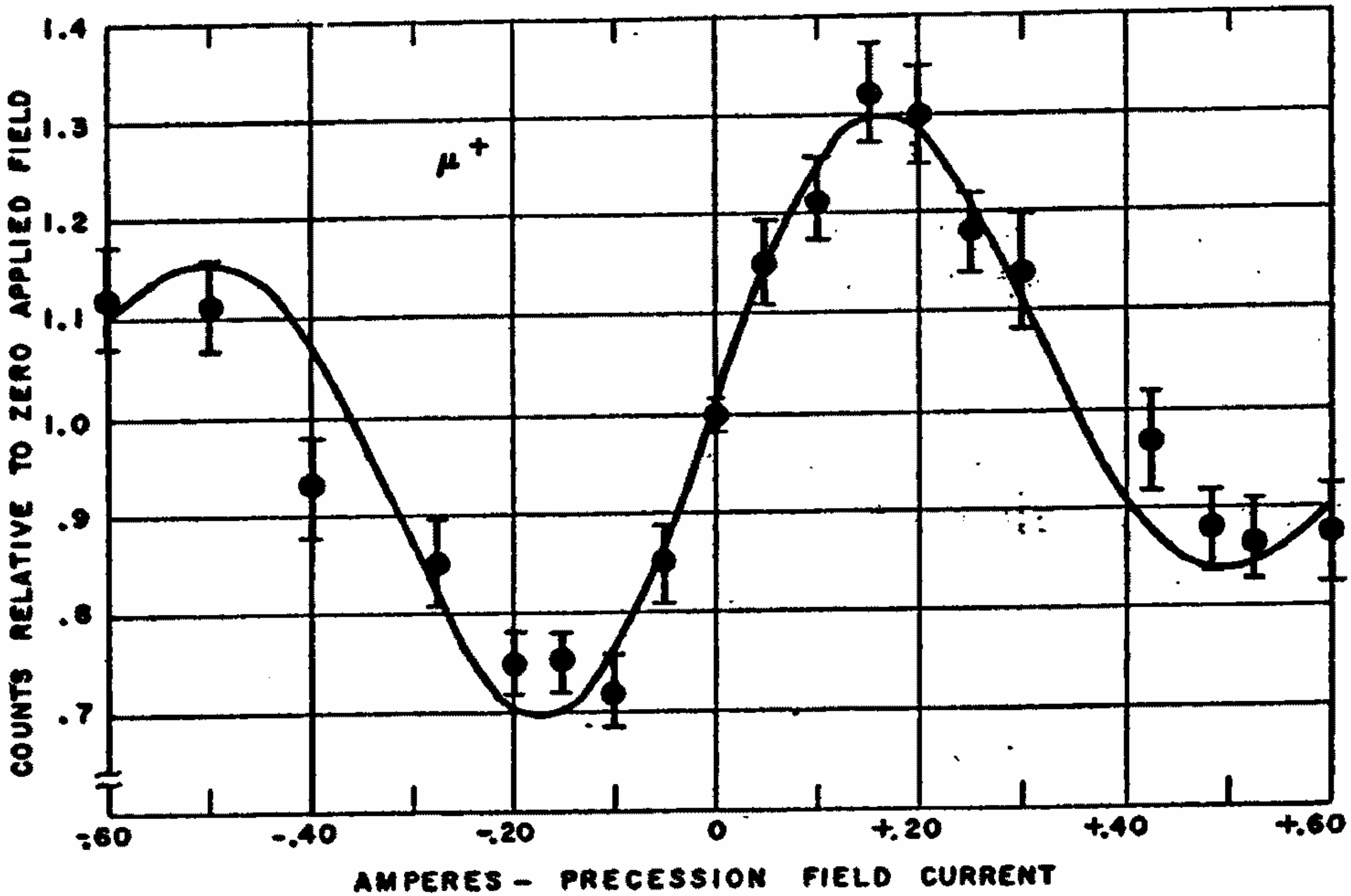

Fig. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

Many papers at www.fas.org/RLG but not yet those shown in this presentation. See, however,

- "Fun With Muons, GPS, Radar, etc.," by R.L. Garwin, Lee Historical Lecture, Harvard University, March 18, 2003 or
- "Pief's Contributions to Arms Control and Nuclear Disarmament," by R.L. Garwin, Panofsky Lecture, XVI Amaldi Conference, Hamburg, Germany, March 14, 2008.

A useful tip for you and the children

Not rising to the level of $\mathbf{e^{i\pi}+1=0}$ *but nevertheless useful is the Google tip to go straight to the desired document by putting in the Google searchbox:*

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site:fas.org/rlg/ Garwin missiles Poland (3/655)
site:mda.gov mda missiles Poland (35/50,500)
site:fas.org/rlg/ Garwin Fermi (144/15,900)